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Prevention of coherence collapse in diode lasers by dynamic targeting

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We numerically show that a laser that would suffer from coherence collapse if precautions were not taken can be made to operate with a small linewidth and a stable maximum output power by application of a new dynamic targeting technique.

Optical feedback is a well-known effect that must be taken into account when analyzing the behavior of a semiconductor laser. Even for external reflections of less than 1%, the laser can operate in the coherence-collapse regime characterized by chaotic behavior of the output power and a linewidth increased by a factor of 1000.[1] To prevent such deleterious effects, expensive and nonintegrable optical isolators have to be used.

It was already concluded from theory in 1990 that, under conditions of coherence collapse (or, for that matter, conditions of low-frequency fluctuations),[2] stable operation with high power and narrow linewidth should occur.[3] Recently, this property was rederived by an asymptotic approximation technique,[4] and the physical consequences were discussed.[5] To our knowledge, no experimental observations of this narrow-linewidth steady-state operation have been reported yet, which indicates that it is unlikely for the system to be captured in the corresponding basin of attraction. In this respect and to avoid possible confusion, the experimental work of Dahmani *et al.*,[6] who obtained stable operation of a diode laser by using a resonant Fabry–Perot cavity as an external feedback mirror, is noteworthy. However, in their experiment the frequency selectivity of the external system along with the moderately strong feedback give the system dynamical properties different from those of the system under consideration here: a diode laser with frequency-independent external feedback. Instead of adding a special device (like an optical isolator or an external resonator), the challenge taken on here is to identify a certain switch-on protocol that makes the system operate in a stable mode at the end of the manipulation process. After application of this protocol, the laser should be able to maintain stable operation all by itself, with a reduced linewidth and maximum output power. Note that the targeting protocol proposed here is not a chaos-control technique. In chaos control, one attempts to force the system to operate in an unstable orbit[7] by some sort of small correctional feedback,[8] whereas in our case we attempt to deliver the system in a stable fixed point that cannot be reached when the laser is left by itself.

A single-mode semiconductor laser subjected to weak to moderately strong feedback (approximately 10^{-6} to 10^{-2} of the emitted light is fed back) can be described in terms of the Lang–Kobayashi equations[9]:

$$\dot{E}(t) = \frac{1}{2}(1 + i\alpha)\xi n(t)E(t) + \gamma E(t-\tau) \times \exp(-i\omega_0\tau) + F_E(t), \tag{1}$$

$$\dot{n}(t) = (p-1)J_{\text{th}} - \frac{n(t)}{T_1} - [\Gamma_0 + \xi n(t)]P(t) + F_N(t), \tag{2}$$

for the slowly varying amplitude of the electrical field $E(t)$ and the carrier number (with respect to the solitary laser value N_0) n. γ and τ are the feedback rate and the delay time, respectively; ω_0 is the solitary laser frequency; α is the linewidth enhancement factor; p is the pump current in units of threshold current J_{th}. F_E and F_N are Langevin forces describing a (Gaussian) white-noise process that represents random fluctuations caused by spontaneous emission with rate R. The equations are normalized such that $P = |E|^2$ is the number of photons inside the cavity. The definitions of the other parameters and their typical values are listed in Table 1.

The time-independent solutions of the Lang–Kobayashi equations lead to fixed points that are created in subsequent saddle-node bifurcations with increasing feedback rate; such points are usually called external cavity modes and antimodes.[10] The antimodes are (unstable) saddle points. The stability of the modes depends on, among other things the feedback parameter $C = \gamma\tau\sqrt{1+\alpha^2}$. In the weak feedback regime (small-C) modes are stable, and the laser operates in the minimum linewidth mode for which the frequency shift is closest to the solitary laser frequency.[11] For increasing C values many modes become unstable spiraling saddle points because of Hopf bifurcations.[4] Physically, the modes tend to show undamped relaxation oscillations, and the laser is observed to jump among many of these unstable modes.[12]

It was recently reported that, while one is increasing the feedback rate, the creation of a new mode on the low-frequency (maximum power) side, derived from a saddle-node bifurcation, always takes place before the mode that is created last loses stability in its Hopf bifurcation.[5] This result is referred to as the stability of the maximum gain mode (MGM).[5] With respect to the solitary laser, this MGM, characterized by the frequency shift $\Delta\omega_s^{\text{MGM}} = -\gamma\tau\alpha$, has the

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Table 1. Definitions and Values of the Different Parameters Appearing in the Model

Parameter	Definition	Value	Units
Γ_0	Decay rate of the photons	0.357	ps^{-1}
ξ	Differential gain	2.14×10^4	s^{-1}
N_t	Carrier number at transparency	1.54×10^8	–
α	Linewidth enhancement factor	5.1	–
T_1	Carrier lifetime	1.1	ns
R	Spontaneous emission rate	10^{12}	s^{-1}
J_{th}	Threshold current	22.7	mA
ω_0	Angular frequency of the solitary laser	1.216×10^{15}	ps^{-1}

maximum output power and a reduced linewidth $\Delta\lambda^{\mathrm{MGM}} = \Delta\lambda_0/(1 + \gamma\tau)^2$,[5] where $\Delta\lambda_0$ is the linewidth of the solitary laser. Usually, for large C values, not just the MGM but rather a set of modes in its neighborhood is stable. However, because of the small basin of attraction of these stable modes, the probability that the laser will reach them by itself is negligibly small. In any case, this result has never been positively observed in experiments or in simulations, to our knowledge. If moderately strong feedback is present during switch-on, the single-mode semiconductor laser will show low-frequency fluctuations or even more chaotic behavior (coherence collapse[1]), depending on the pump current. We numerically show that a diode laser with optical feedback can be made to operate in one of the stable modes near the MGM. Our targeting method is based on gradually increasing the feedback level from zero while adjusting the feedback phase $\omega_0\tau$ in a prescribed way. This mechanism enables us to maintain the system operating in the region of stable modes around the MGM.

The general idea of our approach is as follows. First we prepare the system in a stable fixed point. Then we slowly change the external parameters γ and $\omega_0\tau$ in such a way that the system follows the parameter variations. This can be done in practice by use of suitable acousto- and electro-optical modulators. When varying the external parameters γ and $\omega_0\tau$, we cause the fixed points to move in phase space along with their associated basins of attraction. If the motion is slow enough, the system will stay within the moving basin of attraction. Two difficulties remain. The first is that the system should be in a stable mode when the protocol starts. The solution of this problem lies in the fact that for very low feedback a laser has only one stable mode with the whole phase space as its basin of attraction. The second problem is that the mode in which the system operates should remain stable while moving through phase space. We choose to increase the feedback rate γ linearly in time from zero to a final value γ_f while moving the mirror continuously, so that $\omega_0\tau = \gamma\tau\alpha \bmod 2\pi$ at all times. This protocol ensures that the mode in which the system with feedback operates moves continuously through phase space. Moreover, this mode will always be the MGM and thus will always to stable.[5]

This mechanism can be better understood with the help of the potential picture introduced by Mørk *et al.*[13] Figure 1 illustrates how the modes and the antimodes, represented by the local potential minima and maxima, respectively, are created when γ is increased and how they move when $\omega_0\tau$ is changed. Here we assume that we can vary $\omega_0\tau$ independently from τ. This will be the case if the necessary changes in τ, which are made so as to change $\omega_0\tau$, are small compared with τ, i.e., for large external cavities.

Figure 2 shows the output power of the laser as a function of time during the targeting protocol. The system remains stable in the neighborhood of the MGM. Once γ and $\omega_0\tau$ have reached their final values, the laser emits with maximum output power. Moreover, the theoretical reduction of the linewidth amounts to $(\Delta\lambda^{\mathrm{MGM}})/\Delta\lambda^0 \sim 10^{-5}$. However, this figure has to be judged with care, since in practice mechanical noise in the external system will have taken over at some point.

The rate of changing γ is not arbitrary but is bounded from two sides: the maximum rate is set by the ability of the system to follow the motion of the stable mode through phase space. The minimum rate is given by the mean escape time from the well. Both rates can be estimated from the potential picture already mentioned. In the potential model the round-trip phase difference η satisfies[13]

$$\frac{\mathrm{d}\eta}{\mathrm{d}t} = -\frac{1}{\tau}\frac{\mathrm{d}}{\mathrm{d}\eta}U\,, \tag{3}$$

where the potential U is defined by

$$U = \eta^2 - 2C\cos(\omega_0\tau + \arctan\alpha + \eta)\,. \tag{4}$$

Notice that we have a time-dependent potential, since the parameters C and $\omega_0\tau$ now depend on time. The

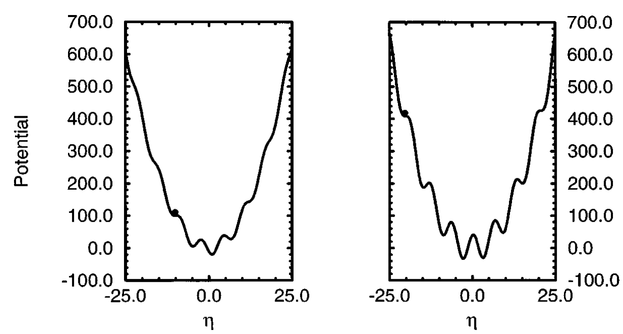

Fig. 1. Qualitative picture of the potential for two different values of γ and $\omega_0\tau$. The filled circle on each curve represents the position of the system in the maximum gain mode. Parameters are $\alpha = 5.1$, $\tau = 2.0$. Left: $\gamma = 1.0\ \mathrm{ns}^{-1}$, $\omega_0\tau = 10.2$; right: $\gamma = 2.0\ \mathrm{ns}^{-1}$, $\omega_0\tau = 20.4$.

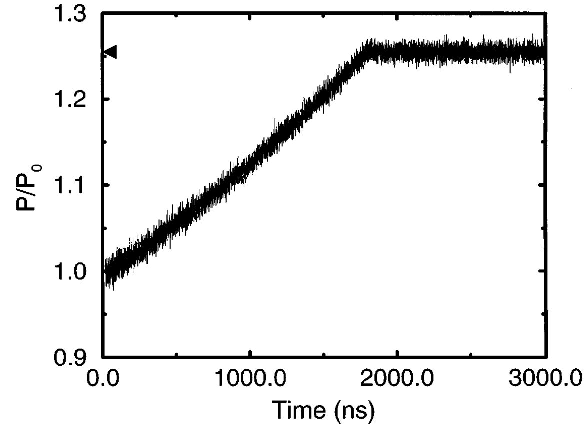

Fig. 2. Numerical simulation of the time evolution of the output power normalized to the output power without feedback for a rate of change of γ of 0.02 ns^{-2}. The feedback parameters are $\tau_0 = 10$ ns, $\gamma_f = 35\ ns^{-1}$, $\omega_0(\tau_f - \tau_0) = -1785$, injection current $J = 75$ mA (threshold current of 25 mA), and linewidth enhancement factor of 5.1. The output power of the MGM is indicated by the triangle, top left.

approximations made in deriving this model are still valid, provided that C and $\omega_0\tau$ are varied slowly. We demand that the system remain inside the moving potential well of the MGM. Since the rate of change of the MGM is $-\tau\alpha\dot{\gamma}$, this leads to $d\eta/dt \sim -\tau\alpha\dot{\gamma}$. As $d\eta/dt$ is limited by the maximum slope of the potential U inside the MGM well, the restriction on $\dot{\gamma}$ is now

$$\frac{d\gamma}{dt} < \dot{\gamma}_{\max} = \frac{2}{\alpha\tau^2}\left[(2k_{\mathrm{MGM}} + 1)\pi - \arccos\frac{1}{C} - \omega_0\tau - \arctan\alpha + \sqrt{C^2 - 1}\right]. \qquad (5)$$

The integer k denotes which local maximum of $dU/d\eta$ has been taken.

As long as Eq. (5) is obeyed, the system will be able to follow the motion of the mode through phase space. Notice that $\dot{\gamma}_{\max}$ increases with time because the potential wells get steeper with increasing γ. If $\dot{\gamma} > \dot{\gamma}_{\max}$ for a sufficiently long time, the system will drop back one or more modes until it has reached a stable mode in which $\dot{\gamma}$ does not exceed $\dot{\gamma}_{\max}$ or until it reaches the chaotic region (coherence collapse).

It usually happens that, at the start of the protocol, only a few modes are available, all corresponding to shallow potential wells. This means that the system can easily be kicked out of a well because of spontaneous emission noise. One can estimate the mean escape time from any particular well by following the calculations reported in Ref. 14. For large values of the feedback parameter C, the escape time is virtually infinite. For small value of C, the system is almost always observed to jump from the MGM to the mode below the MGM as soon as this mode is created. Fortunately, in almost all cases this mode is also stable, and its potential well is much deeper than the MGM. Nevertheless, the mean escape time may still be small enough to cause more jumps so as to enter the chaotic region. Therefore the protocol can be successful only if the laser operates during a sufficiently short time in the low-feedback regime ($C \sim 1$), i.e., a time that is small compared with the mean escape time. This implies a minimum rate of change, which, to be indeed smaller than the maximum rate given by Eq. (5), limits the applicability of our protocol to systems with pump currents that are sufficiently large (for our parameters $p \gtrsim 1.5$).

In conclusion, we have numerically shown that a single-mode semiconductor laser with external optical feedback, which without precaution would suffer from low-frequency fluctuations or coherence collapse, can operate in a stable regime. This can be achieved by application of a new dynamic targeting protocol based on the manipulation of the external feedback parameters. This new technique can be used to obtain the first, to our knowledge, experimental demonstration of the intriguing coexistence of coherence collapse and stable operation in a diode laser with optical feedback. It may thus prove to be a simple way to achieve narrow-linewidth operation by use of weak to moderate feedback and may even lead to a cheap alternative for the use of optical isolators in optical communication systems.

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References

1. D. Lenstra, B. H. Verbeek, and A. J. den Boef, IEEE J. Quantum Electron. **QE-21,** 674 (1985).
2. J. Mørk, B. Tromborg, and P. L. Christiansen, IEEE J. Quantum Electron. **24,** 123 (1988).
3. B. Tromborg and J. Mørk, IEEE Photon. Technol. Lett. **2,** 549 (1990).
4. T. Erneux, G. H. M. van Tartwijk, D. Lenstra, and A. M. Levine, Phys. Rev. A. (to be published).
5. A. M. Levine, G. H. M. van Tartwijk, D. Lenstra, and T. Erneux, Phys. Rev. A **52,** R3436 (1995).
6. B. Dahmani, L. Hollberg, and R. Drullinger, Opt. Lett. **12,** 876 (1987).
7. E. Ott, C. Grebogi, and J. A. Yorke, Phys. Rev. Lett. **64,** 1196 (1990).
8. R. Roy, Z. Gills, and K. Scott Thornburg, Opt. Photon. News **5**(5), 8 (1994).
9. R. Lang and K. Kobayashi, IEEE J. Quantum Electron. **QE-16,** 347 (1980).
10. T. Sano, Phys. Rev. A **50,** 2719 (1994).
11. K. Petermann, *Laser Diode Modulation and Noise* (Kluwer, Dordrecht, The Netherlands, 1988).
12. C. R. Mirasso, M. Mulder, H. J. W. Spoelder, and D. Lenstra, Comput. Phys. (to be published).
13. J. Mørk, S. Semkow, and B. Tromborg, Electron. Lett. **26,** 609 (1990).
14. D. Lenstra, Opt. Commun. **81,** 209 (1991).